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THE USE OF ELECTRICAL DISCHARGE FOR IGNITION AND CONTROL OF COMBUSTION OF SOLID PROPELLANTS

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The Use of Electrical Discharge for Ignition and Control of Combustion of Solid Propellants

1. Introduction

It is a well known problem to interrupt and re-start combustion of solid propellant in order to control the thrust of a solid propellant rocket. Many investigations have been made in combustion interruption by rapid pressure reduction or combustion restrainer injection in the combustion chamber. There have been experiments on ignition and combustion control by injecting a reactive liquid into combustion chamber[1)–3)].

We have been investigating the combustion control of solid propellant by electrical discharge. Namely the combustion can be started and maintained by an arc discharge current flowing along the surface of solid propellant. The combustion speed can be controlled by changing the arc current. Enthalpy of the combustion product can be increased by the arc electrical energy. Although the idea of combustion control by the arc discharge was proposed earlier[4)], no experimental investigations have been made. In this report, experimental results of the arc discharge effects on solid propellant combustion will be described. The arc discharge can be used for the ignition of a solid propellant; its performance characteristics will be described as well.

2. Solid propellant and the experimental setup.

All the experiments reported here were made at atmospheric pressure. Usual propellant for solid rocket (Table 1, No. 1) as well as the following special propellants were used.

A propellant was made by compressing a mixture of aluminum powder (80 mesh) and teflon powder (200 mesh). This propellant has characteristics so that ignition and combustion can be controlled by an arc current. The heat generation of this propellant is due to the following reaction of florine and aluminum from teflon pyrolysis,

$$C_2F_4 \rightarrow 2C + 2F_2 \qquad -157kcal/mol,$$

$$Al + 3/2F_2 \rightarrow AlF3 \qquad +361kcal/mol.$$

	1) 組成	2) 発熱量 (J/g)	密度 3) (g/cm³)	
No. 1	PB/Al/AP	5870	1.76	自燃性† 4)
No. 2	Al 10%/$(C_2F_4)_n$ 90%	−1760*	2.16	自己消火性† 5)
No. 3	Al 20%/$(C_2F_4)_n$ 80%	5950*	2.22	自己消火性† 5)
No. 4	Al 30%/$(C_2F_4)_n$ 70%	12160*	2.28	自燃性† 4)

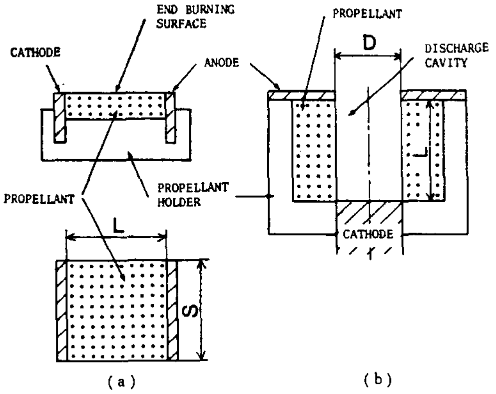
* C と F_2 の再結合のない場合 6)
† 周囲圧力 1 気圧の場合 7)

Table 1. Propellants used in the experiment.

1) Composition, 2) Calorific value, 3) Density, 4) Spontaneous combustion, 5) Non-spontaneous combustion, 6) without recombination of C and F_2, 7) at atmospheric pressure.

Although the present report will limit the description to the experimental results of ignition and combustion control, this propellant is known to generate relatively high calorie under appropiate combustion condition[5]. As expected from the above reaction equation, in order to increase the generated calorie, enough aluminum must be mixed to react with F_2. However, the Al mixture is limited to 30% due to the reduction of propellant strength. In the experiment, three types of $Al/(C_2F_4)_n$ were used as shown in Table 1 No. 1, 2, and 3. The calorific values of No. 2, 3, and 4 given in Table 1 were calculated assuming that teflon sublimates to C and F_2, and F_2 reacts with Al yielding AlF_3. The calorific value is given by generated heat in the reaction of F_2 and Al subtracting the heat required in sublimation.

Fig, 1(a) and (b) show propellant and electrode arangement for end-burning and internal burning cases, respectively. The distance (L) between electrodes was fixed at 8 mm. Fig. 2 shows the circuit to supply arc discharge current, consisting of a direct current power supply with variable voltage (V_s) and a variable resistor (R_i) which changes the arc current. Average combustion speed was calculated from the propellant weight and the combustion duration.



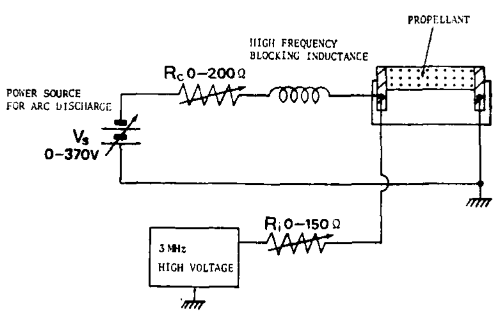


Fig. 1 Arrangement of propellant and electrodes for (a) end-burning and (b) internal-burning.

Fig. 2 Circuit for the arc current supply.

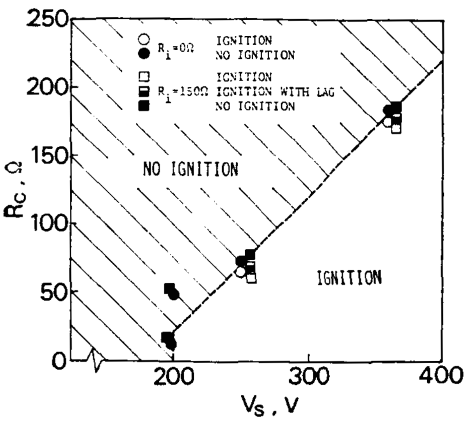
In this experiment propellant ignition by arc discharge was also tried using the same electrodes. Namely, an appropriate voltage was applied on the electrodes by the arc discharge power supply, and the arc discharge was generated by applying high frequency high voltage (3 Mhz, modulated by 100 Hz) on the electrodes. This arc discharge was used to ignite the propellant as well as to change combustion speed and to increase enthalpy of the combustion gas.

3. Results of the experiment - 1 (ignition).

The ignition method presently used for solid propellant has a multi-step mechanism. Namely, an electrical heat ignites an initial explosive which in turn ignites a primary explosive which then ignites the propellant. It is more complex to ignite solid propellant directly using an arc discharge. Iihara *et al.*[6] has investigated an ignition possibility using a single or continuous spark discharge, and obtained the following results: 1) The discharge ignition of solid propellant requires a relatively large discharge energy (at the same time the propellant must be protected against an accidental discharge.) 2) For continuous pulse discharge, there is quite a long time lag in ignition. 3) It is easier to ignite propellant when an arc discharge is made in a cavity surrounded by propellant rather than on a propellant surface[6]).

In order to be able to use the same electrode for both ignition and combustion control experiments, an ignition method using arc discharge induced by a high frequency high voltage is adopted. Experimental results on the ignition characteristics will be described below.

Fig. 3 shows the ignition limit for the propellant No. 1 (composite propellant commonly used in solid rocket) in the end-burning condition. The figure shows the discharge current control resistance (R_c) as a function of the arc discharge voltage (V_s). As seen from the figure, for a lower voltage V_s, a smaller R_c is necessary to ignite the propellant. The propellant never ignited below 200 V. Decreasing the arc discharge power of the high frequency discharge did not change the ignition limit R_c, but it caused a time lag of ignition. This time lag was not the same even with the same experimental condition and varied 0-3 seconds.



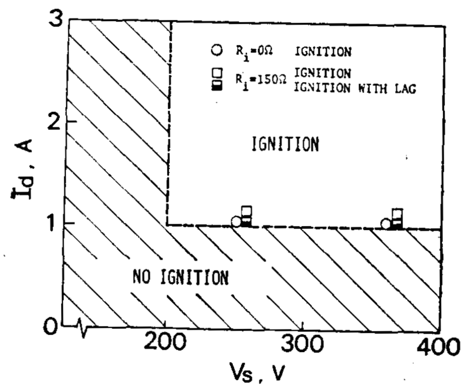


Fig. 3 Ignition limit by arc discharge.

Fig. 4 shows the discharge current I_d at the ignition limit R_c as a function of the arc discharge voltage. The discharge current at the ignition limit did not depend on the discharge voltage. For a range 1-20 A of the discharge current after the ignition, the discharge voltage stayed constant at about 200 V. This may be related to the fact that the ignition was impossible below 200 V.

Fig. 4 Ignition limit by arc discharge.

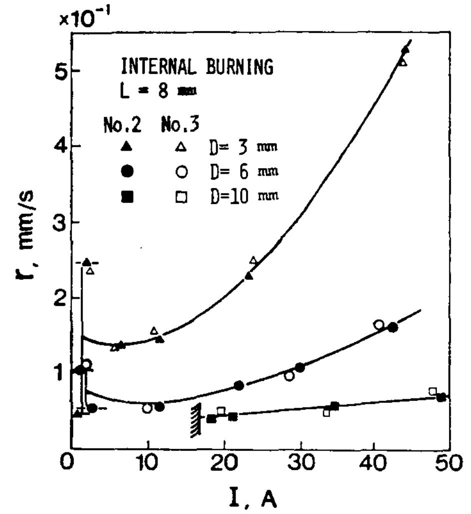
Although detailed explanation of the ignition mechanism requires future investigations, energy required for the ignition will be estimated in the following. Energy of the high frequency arc discharge was measured by a calorimeter to be about 5.0 W without damping resistor (R_i=0) and 2.4 W with 150Ω damping resistor. The arc discharge time can be measured by interrupting the discharge current and inspecting the propellant whether the combustion has started or not. With a discharge current 1.5 A, the time was 0.02 seconds, and the required ignition energy was calculated to be 6 J which is consistent with the value reported in ref. 6). It is well known that the combined system of arc discharge and high frequency discharge with high breakdown voltage has a good characteristics for ignition of flammable gas. The present experiment shows that the similar system also works for ignition of solid propellant[7)].

The results shown in Fig. 3 and 4 were obtained for propellant commonly used in solid rocket. With other propellants $Al/(C_2F_4)_n$ developed for this experiment, ignition became more difficult and ignition time lag also appeared more frequently. As reported in ref 6), it is more difficult to ignite propellant in the end-burning condition than in the internal-burning condition.

4. Experimental results -2 (combustion control).

Combustion control can be made for $Al/(C_2F_4)_n$ composite propellants No. 2 and 3 by an arc discharge current flowing along the propellant surface. Combustion control is not possible for the the propellant No. 4 because combustion of this propellant can not be suspended.

Fig. 5 and 6 show the experimental results for the internal-burning condition (No. 2 and 3) and the end-burning condition (No. 2), respectively. The ignition was not possible at the arc discharge current below 2 A. Above this current, combustion could be started or suspended by the discharge current flow. The combustion speed r increased with the arc discharge current. As seen in Fig. 5, the $r - I$ relation for the propellants No. 2 and 3 are almost identical. This is explained by the fact that the pyrolysis in the propellant surface is induced by the arc discharge energy and its speed is controlled by the pyrolysis speed of teflon. Results for the propellant No. 3 is not shown in Fig. 6 because ignition was not possible with the present method. For the propellant No. 4, the combustion could not be controlled by the arc discharge current for the internal-burning condition.



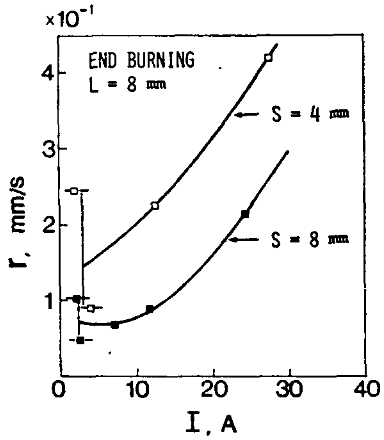
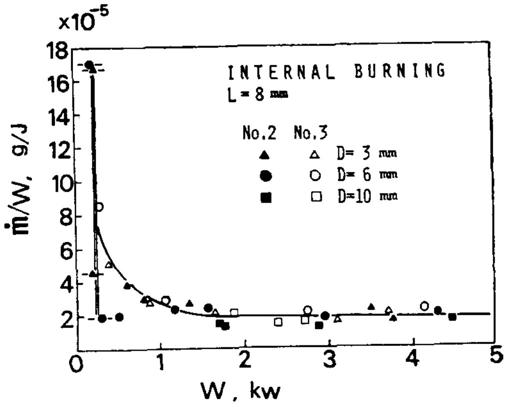


Fig. 5 Relation between arc current I and propellant line combustion speed r (internal-burning, No. 2, No. 3).

Fig. 6 Relation between arc current I and propellant line combustion speed r (end-burning, No. 2).

Fig. 7 and 8 show the propellant combustion rate $\dot{m}/W$ as a function of arc discharge power W. The $\dot{m}/W$ value is large at a small discharge power, but it approaches to a constant at large W.



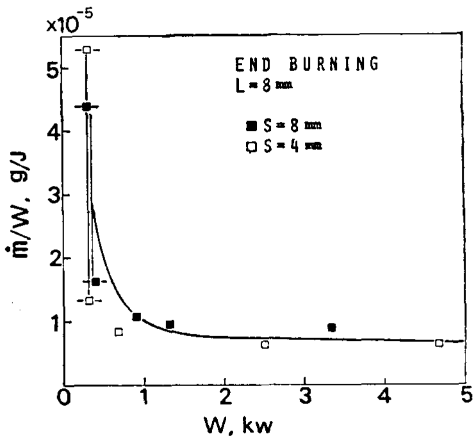


Fig. 7 Relation of arc discharge power W and propellant mass combustion rate $\dot{m}/W$ (internal-burning, No. 2, No. 3).

Fig. 8 Relation of arc discharge power W and propellant mass combustion rate $\dot{m}/W$ (end-burning, No. 2).

The ratio of generated chemical energy and arc discharge power can be expressed by $Q\dot{m}/W$ in terms of calorific value Q per unit propellant weight. In order to control combustion using arc discharge, this ratio needs to be large. But to increase enthalpy of the combustion product, a smaller ratio is more desirable. For internal-burning of the propellant No. 3, $Q\dot{m}/W$ is 0.1 - 0.5 (Q=5950 J/g, $\dot{m}/W=1.7\text{-}8.0\times10^{-5}$g/J). Since flammable gas combustion is extremely accelerated by a small arc discharge energy[8], it is expected to be able to obtain a large $Q\dot{m}/W$ ratio by finding an appropriate propellant and discharge condition.

Fig. 9 shows effects of the arc discharge on combustion of commonly used composite propellant No. 1 (Pb/Al/AP, self-flammable). The propellant grain has an inner radius 3 mm and an outer radius 7 mm. The average line combustion speed is shown as a function of the arc discharge current. There is a threshold in the arc discharge current for both end-burning and internal-burning conditions. Below this threshold current, the arc discharge current is repelled from the combustion surface by the combustion gas flow, and the arc discharge energy is spent to heat the combustion gas.

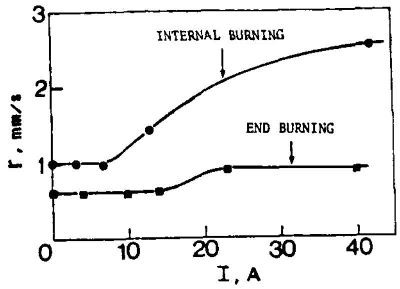


Fig. 9 Relation between arc discharge current I and propellant line combustion speed r (No. 1).

5. Summary.

It was shown in this experiment that a combined system of high frequency electrical discharge and direct current arc discharge has good characteristics for ignition of solid propellant. For commonly used propellant, once the combustion is started, it can not be interrupted even if the arc discharge is stopped. However, for the specially made propellant (No. 2 and 3) for this experiment, combustion can be controled by the arc discharge. There are two typical effects of arc discharge on propellant combustion; namely, effect on propellant pyrolisis and heating of combustion product.

High temperature gas jet produced by sublimation of solid propellant by arc discharge and chemical reaction of the gas produced by the sublimation can be used as a high temperature heat generator in place of usual plasma jet. Applications of this system for solid rocket ignition or secondary propulsion rocket motor (electrical heating type) are limited due to the limitation of arc discharge frequency and relatively large power requirement.

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16. Abstract
As the first step of the study of combustion control of solid propellants by electrical discharges, the effects of an arc discharge, which flows along the burning surface, on the burning rate and on the increase of enthalpy of the combustion product were investigated. For specially devised composite propellants, which are composed of Al powder and teflon powder, it was shown that the combustion can be controlled by an arc discharge; the combustion continues when the arc discharge is applied and is interrupted when the arc discharge breaks. In the present investigation, it was also shown that an arc discharge coupled with a high frequency electrical discharge has potentiality as an effective ignition method for solid propellants. For the use of this type of combustion control to an ignitor for a solid propellant rocket motor or to a control rocket motor, this method lacks flexibility in the configuration scale and needs a relatively large electric power at present stage.

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